

## **D. Intermediate-Rate Crush Response of Crash Energy Management Structures**

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### **Objectives**

- Develop unique characterization facility for controlled progressive crush experiments, at intermediate rates, of automotive materials (polymer composites, high-strength steels, and aluminum) and structures.
- Study the deformation and failure mechanisms of automotive materials subjected to crush forces as a function of impact velocity.
- Obtain specific energy absorption and strain data, and correlate with deformation and failure mechanisms to describe the unknown transitional effects from quasi-static to high loading rates for polymer composites.
- Characterize the strain rate effects for metallic materials and components.
- Provide access to unique test capability to university, industry, and government users for collaborative research.

### **Approach**

- Develop a unique high-force (270-kN), high-velocity (8-m/s) servo-hydraulic machine to conduct progressive crush experiments on structural components at intermediate rates.
- Use high-speed imaging to observe and document deformation and damage mechanism during the crush event.
- Conduct strain measurements at discrete locations and explore full-field measurements of strains and curvatures.
- Coordinate polymer composites investigations with the Automotive Composites Consortium (ACC) Energy Management Group.
- Coordinate steel investigations with the Automotive/Steel Partnership.

## Accomplishments

- Completed design modification and fabrication to achieve increased performance (125%) up to 8 m/s.
- Completed installation and initial operator training at the National Transportation Research Center (NTRC).
- Completed new acceptance tests on-site to demonstrate enhanced performance.
- Completed design and fabrication of test fixtures for testing five different tube geometries.
- Completed integration of high-speed data acquisition with test operation.
- Completed vendor demonstrations on four high-speed video systems.
- Completed a total of 38 shakedown tests as part of high-speed video assessments, capability demonstrations, and machine commissioning.
- Held official dedication ceremony in August 2003.
- Completed 60 tests to characterize glass fiber composites tubes at 5 different velocities.
- Completed carbon-fiber tube and strip tests for Ford Motor Company under the User's Facility Agreement.
- Completed parametric studies on tuning parameters to qualitatively and quantitatively determine their effect on the velocity drive file.
- Completed full-field measurement demonstration using digital image correlation techniques.
- Completed 47 tests on steel tubes in support of the Auto/Steel Partnership Program.

## Future Direction

- Procure high-speed video.
- Explore techniques for full-field measurements of strains and curvatures.
- Develop User Interaction Plan.
- Support user collaboration as required.

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## Introduction

Progressive crush is an important mechanism by which the kinetic energy of a traveling automobile is dissipated in a collision to protect the safety of occupants. Unfortunately, the mechanisms governing the progressive crush response of some emerging automotive materials are not well understood. Additionally, many of these materials are known to exhibit responses that are sensitive to rate of loading.

Understanding the influence of impact velocity on the crush response of materials and structures is critically important for crashworthiness modeling inasmuch as collisions occur at a range of velocities. Additionally, from a structural standpoint, the deformation (or strain) rate is generally not unique from either a spatial or temporal standpoint. Consequently, it is important to quantify the behavior of materials at various strain rates.

## Test Machine for Automotive Crashworthiness (TMAC)

Typically, standard test machines are employed for experiments at quasi-static rates, whereas drop towers or impact sleds are the convention for dynamic rates. These two approaches bound a regime within which data, for experiments at constant impact velocity, are not available by conventional experimental practice. This regime is termed herein the intermediate-rate regime and is defined by impact velocities ranging from 1 m/s to 5 m/s. Investigation of rate effects within this regime requires experimental equipment that can supply a large force with constant velocity within these rates. Using a drop tower or sled at intermediate rates, although technically possible, is problematic due to the prohibitively large mass required to maintain constant velocity during the crush. Consequently, the Oak Ridge National Laboratory (ORNL) and the Automotive Composites Consortium (ACC) collabo-

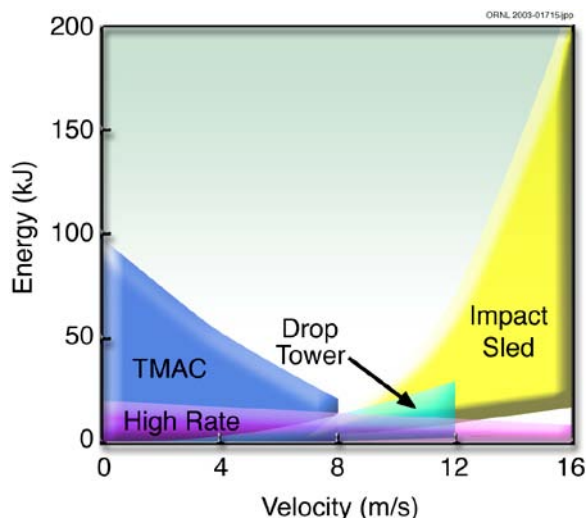
rated to define specifications for a unique experimental apparatus that mitigates the shortcomings of existing equipment. MTS Systems Corporation designed and built the servo-hydraulic test machine, referred to as the TMAC. As shown in Figure 1, TMAC is uniquely capable of conducting controlled progressive crush tests at constant velocity in the intermediate velocity range (i.e., less than 5 m/s) because of the large energy available at those rates and to the sophisticated simulation and control software that permits velocity uniformity to within 10%.

The new experimental facility will be used to understand the crush behavior between the static and dynamic (8-m/s) conditions. The installation of the TMAC at its National Transportation Research Center (NTRC) Knoxville, Tennessee, location is shown in Figure 2.

### Status

Since the last reporting period, a set of baseline cases were run using the Advanced Drive File Generator (ADFG). The purpose of these dry-fire tests, that is, tests without specimens, was to archive the machine performance for future maintenance checks and/or troubleshooting. Cases from 1 m/s up to 8 m/s were run with various initial accelerations.

After completing the baseline cases, parametric studies were done to determine the influence that different tuning parameters had on generating



**Figure 1.** Energy plot indicating TMAC's unique capability of supplying enough energy at the intermediate rates for controlled, constant-velocity crush tests.



**Figure 2.** TMAC installation at NTRC.

constant velocity profiles. The parameters that were adjusted were the initial acceleration, zero offset, velocity trim, and acceleration trim. It was determined that up to approximately 4 m/s, it was possible to achieve constant velocity profiles without adjusting the baseline parameters and without iterating using the inverse model. Beyond the 4-m/s regime, additional work is required to fully understand the relative effect each parameter has on the ability to achieve a constant velocity profile. It was also apparent that several iterations would be required at these higher velocities to achieve the desired result of a constant velocity over at least a 100-mm crush length.

A test matrix on glass-fiber reinforced composite tubes was completed, and the experimental data were supplied to the ACC. The tubes were approximately 50 mm by 50 mm square and used an internal plug with a radius as an initiator. The test setup is shown in Figure 3. A total of 60 tests were conducted: 6 specimens/velocity/material; and there were 5 velocities (5 mm/s, 1000 mm/s, 2000 mm/s, 3000 mm/s, and 4000 mm/s); and 2 materials (1 braided and 1 fabric). All target velocities were achieved within a  $\pm 3.5\%$  range without having to iterate or define a specimen. By using a revised test setup that moved the specimen higher up in the load train, the constant velocity was achieved over a 140-mm crush length. All of the drive files were created by trying different initial accelerations for the different test velocities and conducting dry-fires to compare the physical response with the expected response. The experimental data are currently being analyzed and reviewed by the ACC. Photographs that depict typical failure modes for this composite are shown in Figures 4 and 5. Figure 4 was actually taken during a test at the quasi-static rate of 5 mm/s. A typical force and velocity vs time plot is shown in Figure 6 for a 4000-mm/s test.

The first User Facility Agreement for work on TMAC was completed. This work was performed for Ford Motor Company and is described in the following paragraphs.

Characterizing composites for energy management for automotive applications is frequently performed by testing tubular structures. The technical approach for this research was to develop simple coupon tests that quantified the relative energy absorption of each energy absorption mode that was



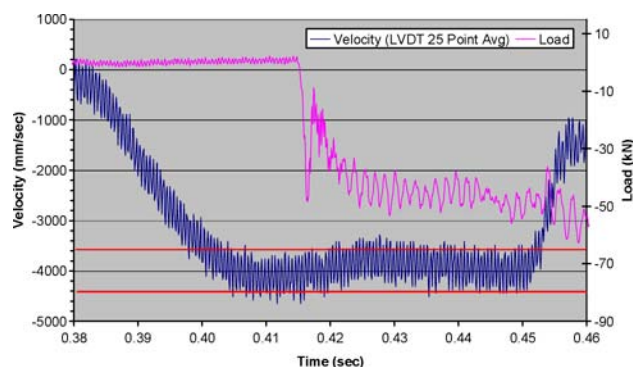
**Figure 3.** Test setup with internal plug.



**Figure 4.** Specimen failure during 5-mm/s test.



**Figure 5.** Progressive crush failure modes in glass-fiber reinforced composite tubes.



**Figure 6.** A 4-m/s velocity profile and force vs time plot of a glass-fiber reinforced composite tube.

identified in the tube tests. Testing would then be performed dynamically and quasi-statically. Ford had already identified the different modes and performed the quasi-static tests, but it needed the dynamic test results to complete the research project.

The testing consisted of crushing square cross section graphite composite tubes at an impact velocity of 2–4 m/s using the TMAC. The test setup is shown in Figure 7. Also, the test plan included crushing graphite composite strips using a test fixture supplied by Ford and adapted for use on the TMAC (see Figure 8). These tests were conducted at the same impact velocity as the tubes. Figure 9 shows a typical failure mode for the composite tubes. The displacement and load data for each test in a format that Ford could process to extract energy absorption was supplied to the Ford engineer that was present on-site during the testing. Ultimately, the data will be used to separate energy absorption due to bending damage of the composite and friction. When these data are compared with the quasi-static data, the goal is to be able to develop a theory



**Figure 7.** Test setup for graphite fiber composite tubes tested under the Ford User Facility Agreement.



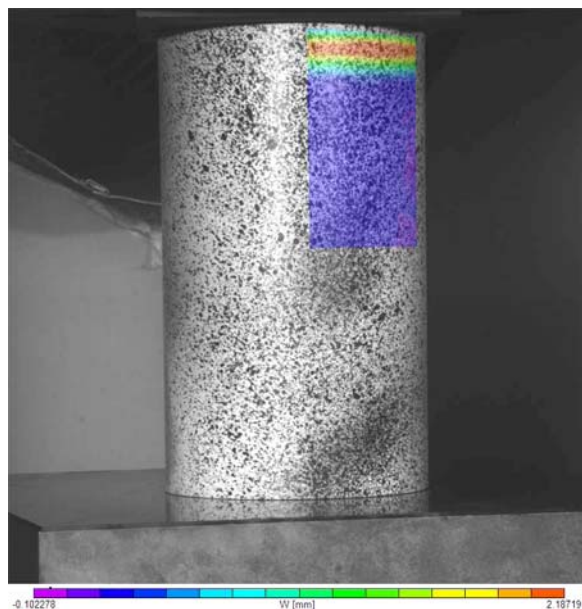
**Figure 8.** Test setup for composite strips tested under the Ford User Facility Agreement.



**Figure 9.** Typical failure for a progressively crushed carbon fiber composite tube.

to explain the difference in specific energy absorption between dynamic and quasi-static tests on otherwise identical test specimens.

The use of digital image correlation techniques as a full-field measurement of strains during dynamic testing was explored by conducting a demonstration. Correlated Solutions completed the demonstration at NTRC in collaboration with Vision Research and their Phantom line of high-speed video cameras. The digital image correlation technique is based on random speckle pattern recognition and tracking the motion of these patterns in space with respect to time. For the out-of-plane displacement associated with a tube crushing experiment, this is a three-dimensional displacement field, and two high-speed cameras are required to resolve the pattern motions. The demonstration was completed using steel tube samples that were approximately 100 mm in diameter and 200 mm long. The specimens were first cleaned and coated with a white flexible coating call SEM Color Coat. They were then oversprayed with a black flexible coating to produce a speckle pattern. Specimens were tested in TMAC and imaged with Phantom high-speed cameras. One Phantom V5 model and one Phantom V7 model were used. Correlated Solutions' software, VIC-3D, was used to reduce the image data to strain and displacement fields. Figure 10 shows an example of the speckle pattern that was sprayed on the tube and then overlaid with a calculated axial strain field resulting from precrushing the tube. The overall results from the demonstration were sufficient to show the capability of VIC-3D for testing with the TMAC.



**Figure 10.** Axial strain in steel tube measured using digital image correlation.

## **Conclusions**

TMAC provides a unique capability to measure the specific energy absorption on crush tubes and other specimen geometries as a function of (constant) impact velocity within a range from quasi-static to 8 m/s.

During the past reporting period, 60 tests were conducted to characterize glass fiber composite tubes at 5 different velocities, and the test data were provided to the ACC. These tests provided critical data in the velocity range of 0.5 to 4 m/s that was previously unavailable using other test methods. Also, carbon fiber tube and strip tests were completed for Ford Motor Company under the first User's Facility Agreement on TMAC. In support of the Auto/Steel Partnership Program, 47 tubes were testing to determine strain rate sensitivities in new high-strength steel alloys.

To gain a better understanding of the TMAC operational characteristics, parametric studies were completed on tuning parameters to qualitatively and quantitatively determine their effect on the velocity drive file. The results showed that iterating on the tuning parameters to achieve a constant velocity profile really becomes an important part of the operation at velocities above 4 m/s. Additional work is required to refine the data acquisition, particularly with regard to comparisons of the two data acquisition cards, filtering of data, and determination of velocity from accelerometer signals.

The full-field measurement technique of digital image correlation was qualitatively demonstrated and showed the potential for being a powerful method of measuring strains in progressive crush experiments at dynamic loading rates.